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Biao Chen

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113 Bowne Hall
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14. ABSTRACT
The objective of the project is to develop a general framework for value driven decentralized information processing. Instead of attempting to identify a unifying information metric for network inference, our approach is to develop a framework that is applicable to various information value metrics as called for by different inference tasks. Major theoretical breakthroughs have been obtained under this effort, including: optimal data reduction in a network setting for decentralized inference with quantization constraint; interactive fusion that allows queries and

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Final Report: Value Driven Information Processing and Fusion

ABSTRACT

The objective of the project is to develop a general framework for value driven decentralized information processing. Instead of attempting to identify a unifying information metric for network inference, our approach is to develop a framework that is applicable to various information value metrics as called for by different inference tasks. Major theoretical breakthroughs have been obtained under this effort, including: optimal data reduction in a network setting for decentralized inference with quantization constraint; interactive fusion that allows queries and interactive information exchange in either tandem or parallel networks; new operational interpretation of Wyner's common information when information loss is inevitable; quantizer design for decentralized estimation; distributed network consensus and multi-agent optimization. The project has enriched the literature in information driven decentralized inference; more importantly, new challenges for inference over networks have been identified that may have broad ramifications in various emerging big data settings when inference is often hampered by practical constraints on information exchange.

A total of five graduate students have worked on research problems related to this project. One of them graduated in August 2013 while three others are expected to graduate this year. Six archival journal papers have been published with three more currently under review/preparation.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
02/25/2016	14.00	Aditya Vempaty, Hao He, Biao Chen, Pramod K. Varshney. On Quantizer Design for Distributed Bayesian Estimation in Sensor Networks, IEEE Transactions on Signal Processing, (10 2014): 0. doi: 10.1109/TSP.2014.2350964
02/25/2016	13.00	Wei Liu, Biao Chen, Ge Xu. A Lossy Source Coding Interpretation of Wyner's Common Information, IEEE Transactions on Information Theory, (2 2016): 0. doi: 10.1109/TIT.2015.2506560
02/25/2016	15.00	Biao Chen, Shengyu Zhu. Quantized Consensus by the ADMM: Probabilistic Versus Deterministic Quantizers, IEEE Transactions on Signal Processing, (4 2016): 0. doi: 10.1109/TSP.2015.2504341
08/26/2014	8.00	Earnest Akofor, Biao Chen. Interactive Distributed Detection: Architecture and Performance Analysis, IEEE Transactions on Information Theory, (2014): 0. doi: 10.1109/TIT.2014.2346497
08/27/2014	9.00	Ge Xu, Shengyu Zhu, Biao Chen. Decentralized Data Reduction With Quantization Constraints, IEEE Transactions on Signal Processing, (04 2014): 0. doi: 10.1109/TSP.2014.2303432

TOTAL: **5**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

02/25/2016 16.00 Shengyu Zhu, Mingyi Hong, Biao Chen. QUANTIZED CONSENSUS ADMM FOR MULTI-AGENT DISTRIBUTED OPTIMIZATION,
IEEE International Conference on Acoustic, Speech, and Signal Processing. 20-MAR-16, . : ,

TOTAL: 1

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
08/27/2014	11.00	Earnest Akofor, Biao Chen. On optimal fusion architecture for a two-sensor tandem distributed detection system, 2013 IEEE Global Conference on Signal and Information Processing (GlobalSIP). 03-DEC-13, Austin, TX, USA. : ,
08/27/2014	12.00	Biao Chen, Pengfei Yang. Wyner's common information in Gaussian channels, 2014 IEEE International Symposium on Information Theory (ISIT). 29-JUN-14, Honolulu, HI, USA. : ,
08/29/2013	1.00	Earnest Akofor, Biao Chen, Shengyu Zhu. Interactive distributed detection with conditionally independent observations, 2013 IEEE Wireless Communications and Networking Conference (WCNC). 07-APR-13, Shanghai, Shanghai, China. : ,
08/29/2013	2.00	Earnest Akofor, Biao Chen. Interactive Fusion in Distributed Detection:Architecture and Performance Analysis, IEEE International Conference on Acoustic, Speech, and Signal Processing (ICASSP). 26-MAY-13, . : ,
08/29/2013	6.00	Shengyu Zhu, Biao Chen. Data reduction in tandem fusion systems, IEEE China Summit & International Conference on Signal and Information Processing. 08-JUL-13, . : ,

TOTAL: **5**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
08/27/2014	10.00	Aditya Vempaty, Hao He, Student Member, Biao Chen, Pramod K. Varshney.. On Quantizer Design for Distributed BayesianEstimation in Sensor Networks, IEEE TRANSACTIONS ON Signal Processing (03 2014)
08/29/2013	3.00	Earnest Akofor, Biao Chen. Interactive Distributed Detection: Architecture and Performance Analysis, IEEE TRANSACTIONS ON Signal Processing (04 2013)
08/29/2013	4.00	Ge Xu, Shengyu Zhu, Biao Chen. Decentralized Data Reduction with QuantizationConstraints, IEEE TRANSACTIONS ON Signal Processing (06 2013)

TOTAL: **3**

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

IEEE Fellow (Biao Chen, 2015)
Fulbright Scholar (Biao Chen, 2014, declined for family reason)
DARPA Spectrum Challenge finalist: Biao Chen (team leader), Kapil Borle, Yu Zhao, and Fangfang Zhu.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Earnest Akofor	0.50	
Pengfei Yang	0.25	
Shengyu Zhu	0.50	
Yu Zhao	0.25	
Ge Xu	0.10	
FTE Equivalent:	**1.60**	
Total Number:	**5**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Biao Chen	0.15	No
FTE Equivalent:	**0.15**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Ge Xu	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Foreword

Statement of the problems studied

Summary of the most important results

Bibliography

S. Zhu and B. Chen, "Quantized consensus by the ADMM: Probabilistic versus deterministic quantizers," to appear in IEEE Trans. Signal Processing, 2016.

G. Xu, W. Liu and B. Chen, "Wyner's common information: generalizations and a new lossy source coding interpretation," to appear in IEEE Trans. Information Theory, 2016.

P. Yang and B. Chen, "To listen or not: distributed detection with asynchronous transmissions," IEEE Signal Processing Letters, vol. 22, no. 5, pp.628-632,May 2015.

E. Akofor and B. Chen, "Interactive distributed detection: architecture and performance analysis," IEEE Trans. Information Theory. vol. 60, pp.6456-6473, Oct. 2014.

A. Vempaty, H. He, B. Chen, and P.K. Varshney, "On quantizer design for distributed Bayesian estimation in sensor networks," IEEE Trans. Signal Processing, vol. 62, no. 20, pp.5359-5369, Oct. 2014.

G. Xu, S. Zhu and B. Chen, "Decentralized data reduction with quantization constraints," IEEE Trans. Signal Processing, vol. 62, pp. 1775-1784, April 2014.

Technology Transfer

The project is primarily focused on theoretical exploration of information driven distributed inference. While discussions of technical nature have occurred with DoD scientists, there have been no patentable disclosure of technology transfer as a result of this project.

Final Report

Value Driven Information Processing and Fusion
Award Number: W911NF1210383

Biao Chen (PI)
Phone: (315)443-3332
Email: bichen@syr.edu
Syracuse University
Department of EECS
121 Link Hall
Syracuse, NY 13244

Submitted to **Dr. Liyi Dai**
Computing Sciences Division
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

March 1 2016

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1 Forward

The objective of the project is to develop a general framework for value driven decentralized information processing. Different from many existing approaches that attempt to identify a single unifying information metric for network inference, our goal is to develop a general framework that is applicable to various information value metrics as called for by different inference tasks. The motivation is that while a plethora of information metrics are shown to be relevant to various inference problems and are themselves connected in an intimate manner, these metrics are not interchangeable. Each of them naturally arises in particular inference problems and the effort of identifying a single metric that applies to all inference problems has so far been fruitless.

A key feature that is common to the numerous research problems addressed under this effort is the impact of practical constraint in a decentralized inference system that may render information loss inevitable. In such situations, the question of how to design a inference network of arbitrary topology, both in the local processing as well as in the information and data flow is not clear.

This project took a two-pronged approach in attempting to address value driven inference over general networks.

1. For the classical networks, including both the tandem networks and parallel networks, we investigate a number of inference problems that are both challenging and significant on their own rights, but are also informative as to how the results may translate into inference problems over general networks. Specific problems under this thrust include sufficiency principle based data reduction for paralell networks under quantization constraint; quantizer design for decentralized estimation over parallel networks; the role of interation and information exchange in tandem and parallel networks; the optimal information flow over a tandom networks for general inference problems; and the applicability of Wyner's common information in various decentralized systems when rate constraints lead to inevitable information loss.

2. For networks of general topology, inference problems are notoriously challenging because of the nested nature of information flow. Additionally, practical constraints such as finite bit information exchange is much more difficult to handle compared with that of simple networks. For this part, we attempt to strive for a deep understanding of the classical network consensus problem, both algorithmically as well as in convergence and consensus error performance. We focus our attention on the ADMM (alternating direction method of multipliers), both due to its fast convergence and its amicability for decentralized implementation. Realizing that many inference problems can be formulated as a consensus reaching problem (e.g., a decentralized detection can be formulated as finding consensus on log likelihood ratio), the analysis will shed light on both the potential approaches and their performance for inference over general networks. Decentralized hypothesis testing over general networks is studied to illustrate how network consensus with quantization constraint can be helpful in attaining optimal error exponents.

While both thrusts have led to important research results, our ultimate goal is to provide a sound approach to the study of inference over general networks with arbitrary topology. The issues identified and investigated using the classical and well structured network, such as the role of interactive fusion and the optimal information flow over those simple networks, have helped inform our approach in addressing inference over arbitrarily connected networks.

Over the course of the project, a total of five doctoral students have worked on research problems related to this project. One of them graduated in late 2013 and has since joined Nuance Communications. Four other doctoral students are expected to graduate within a year. Six archival journal papers have been published with three more that are currently under review/preparation.

The PI is truly indebted to Dr. Liyi Dai for his continued support of this effort. His engaging discussions of various technical aspects of the research effort throughout the project period as well as his effort in reducing the administrative overhead in terms of meetings/presentations on the part of PI have made this project a truly pleasant experience.

2 Statement of Problem Studied

Inference over networks has received attention from various research communities over the past few decades. While classical surveillance applications involving physical sensor networks have been the major impetus in this research area, emerging applications involving both physical and virtual networks have significantly broadened the scope and applications of network inference research.

The research project investigate a number of research problems arising in various application domains. While the problems themselves are diverse in nature, a common thread is the following: while it is desirable to attain inference performance that is lossless in the sense that decentralized inference achieves the same performance, as measured by suitable information metrics, as one where a super-genius has centralized access to the data in the network as well as unlimited computing power, practical constraints often mandate inevitable information loss. The challenge is to design a inference network, both in processing and in information flow such that some optimal performance can be attained in the sense that information loss due to various constraints is kept at minimum. Of particular interest is the so-called quantization constraint where information exchange is often inevitably lossy dictated by the data processing inequality. We list below specific research problems undertaken under the auspices of this award.

- The sufficiency principle is a guiding principle for data reduction for statistical inference. In a decentralized system and when nodes are subject to quantization constraint, there is a need to develop a new framework for data reduction, especially when data dependence is present.

- For a classical two-node tandem network, one may conjecture that information exchange in the form of the so-called interactive fusion may recoup the information loss due to quantization. We show that this is possible only under certain setting. Similarly, in a parallel network with asynchronous transmissions, overhearing other nodes' information may or may not help with the inference performance depending on the data model.

- The design of information flow over linear networks is studied with the goal of optimizing the information value at the terminal node whose choice is itself a design problem. This problem has been studied under the name of communication direction for a two-node network where contradictory results have appeared in the literature. Thus there is a need to reconcile the difference for a clear understanding of how information flow may impact the obtained information value, which is a proxy for the inference performance.

- Decentralized estimation with identical quantizers in a parallel network is practically attractable in its simplicity. We study conditions under which it is also theoretically optimal. In addition, with dependent observations, how data correlation may impact the estimation performance is studied using the Gaussian observation model.

- Network consensus problems when nodes are subject to quantization are studied using the alternate direction method of mutliplier (ADMM) approach. Our emphasis is the analysis of convergence and consensus performance under various practical constraints, e.g., bounded quantizers.

- Decentralized hypothesis testing in general networks is studied where the goal is to show whether or not the optimal asymptotic performance can be attained when nodes are subject to bounded quantization while the data themselves may be unbounded.

3 Summary of the Most Important Results

In the following, we only summarize the most significant results that have the potential to impact future research direction in a meaningful way.

3.1 Interactive Fusion

Existing literature in information fusion almost exclusively assumes a static setting in information flow: nodes propagate information on a directed graph (often in the form of a parallel, tandem, or tree network) and no interaction is assumed or allowed between nodes. We have instead taken a more holistic approach on information fusion where node interaction is allowed in that communications may occur in an interactive manner. Illustrated in Fig. 1 is the contrast between a static fusion system and an interactive one with a two-node tandem network. Note this differs from the traditional study of feedback in tree structure information fusion as we do not limit the number of rounds of interaction and do not restrict it to only between fusion center and peripheral nodes.

We established that [1], with conditional independent observations, while interactive fusion may strictly improve detection performance in the finite sample regime, it has no improvement over the static tandem

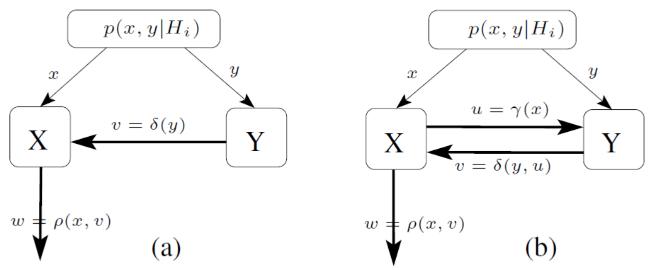

Figure 1: Two node tandem network with (a) static fusion and (b) interactive fusion.

fusion system for the large sample regime. The optimum error exponent, namely the Kullback-Leibler distance, remains the same for both system. However, with conditionally dependent observations, strict performance improvement in both finite-sample and asymptotic regimes are possible.

The study of interactive fusion is based on a simple but elegant result regarding the optimal decision structure for general inference problems with convex or affine objective functions. This simple result has broader applications to inference problems that are beyond the specific problem of interactive fusion. For example, one can establish that for the general tandem fusion system, communication direction should always be in favor of the sensor with high SNR, i.e., it should serve as the fusion center [2].

This interactive fusion framework can be applied to various different fusion systems. In particular, we have studied the simple scheme of sensor overhearing in a simple parallel fusion system where similar results have been established that contrast the system performance with overhearing to that of independent processing at all peripheral nodes [3].

3.2 Data Reduction with Quantization Constraint

The sufficiency principle acts as a guiding principle for data reduction in statistical inference. A sufficient statistic is a function of the data, chosen so that it 'should summarize the whole of the relevant information supplied by the sample. In decentralized settings, a sufficient statistic defined with respect to local data is referred to as a local sufficient statistic; if a collection of local statistics form a global sufficient statistic, they are said to be globally sufficient. While sufficiency based data reduction ensures no loss of inference performance using the reduced data, communicating a one-dimensional real data may still be infeasible when communication is subject to a finite capacity constraint. A question then arises that *if each node in a decentralized inference system has to summarize its data using a finite number of bits, is it still optimal to implement data reduction using global sufficient statistics prior to quantization*?

This is illustrated in Fig. 2 for a two-node parallel system. Observations X_1 and X_2 (each of them is a

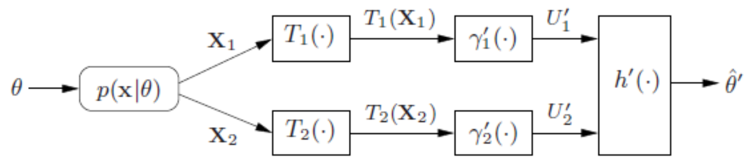

Figure 2: Data reduction in a two node parallel system with quantization constraint.

vector observation of potentially high dimension) are subject to quantization constraint prior to been sent to the fusion center. With conditionally independent observations, i.e.,

$$p(x_1, x_2|\theta) = p(x_1|\theta)p(x_2|\theta)$$

one can establish that sufficiency driven data reduction (i.e., summarizing X_i using a sufficient statistic $T(X_i)$) is still optimal even in the presence of quantizers. However, with dependent observations, the answer is unfortunately *no*, and a simple example is given in [4] that shows globally sufficiency does not guarantee optimal data reduction in the presence of finite-bit quantization which leads inevitably to information loss.

Within the class of conditionally dependent observations, we have identified in [4] that there exist cases where quantizing local sufficient statistics is structurally optimal. Using a simple two node system as an illustration, when $\mathbf{X}_1$ and $\mathbf{X}_2$ are conditionally dependent and θ is the underlying parameter of inference interest, a hidden variable $\mathbf{W}$ can be introduced to induce the following Markov chains hold

$$\begin{aligned} &\mathbf{X}_1 - \mathbf{W} - \mathbf{X}_2, \\ &\theta - \mathbf{W} - (\mathbf{X}_1, \mathbf{X}_2). \end{aligned}$$

Within this hierarchical conditional independence model, first introduced in [5],, if $T_1(\mathbf{X}_1)$ and $T_2(\mathbf{X}_2)$ are local statistics that are sufficient with respect to $\mathbf{W}$, quantizing $T_1(\mathbf{X}_1)$ and $T_2(\mathbf{X}_2)$ at the respective sensor is structurally optimal for the decentralized inference problem. This new framework of decentralized data reduction with quantization constraints has broad applications to numerous inference problems involving networks of sensors and warrants further studies under more general network settings.

3.3 Network Consensus and Quantized ADMM

There have been very limited algorithms for distributed optimization with the quantized communication constraint. Existing quantized algorithms are developed based on the subgradient and only guarantee to reach a neighborhood of the optimal value at a sublinear rate with the error increasing in the size of the network. Recently an ADMM based quantized algorithm, referred to as the quantized consensus ADMM, (QC-ADMM), has been proposed in [7]. A more general result has subsequently been obtained [6] that primarily solves the distributed optimization problem of the following form

$$\arg\min_{x} \sum_{i=1}^{N} f_i(x),$$

where $f_i : \mathbb{R}^M \to \mathbb{R}$ is the local objective function, using only local computation and quantized communication.

The advantage of the proposed algorithm is that, when certain convexity assumptions are satisfied, all $x_{i[Q]}^k$ converge to the same quantization point within $\log_{1+\eta} \Omega$ iterations, where $\eta > 0$ depends on the local objectives and the network topology, and Ω is a polynomial fraction decided by the quantization resolution, the distance between initial and optimal variable values, the local objective functions and the network topology. Furthermore, the consensus error does not depend on the size of the network and is usually smaller than the error of existing quantized algorithms.

While the above algorithm is readily applied to distributed averaging as it is equivalent to a least-squares minimization problem, we notice that the QC-ADMM does not converge uniquely. For locally convergent algorithms, it is well-known that a good starting point usually helps. Based on this fact, [7] proposed a two-stage method which first uses the ADMM with dithered quantization to obtain a good starting point and then employs the QC-ADMM to reach a consensus. Simulations show that the consensus error of this two-stage approach is typically less than one quantization resolution for all connected networks where agents' data can be of arbitrary magnitudes.

This line of work can be readily extended to include cases of more practical significance. For example, with the rounding quantizer assumed above, one still need infinite quantization levels (hence infinite bits for representation) when the input is unbounded. An extension to bounded quantizers with unbounded input has been proposed in [8] where similar convergence results have been established. Perhaps more importantly is the fact that the proposed network consensus approach is much more useful in solving some network inference problem. An example is decentralized hypothesis testing over a network of general but connected topology and it is established in [9] that the developed consensus approach allows a decentralized approach to achieve the optimal error exponent of the centralized counterpart, a conclusion that is significantly stronger than existing results in the literature.

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